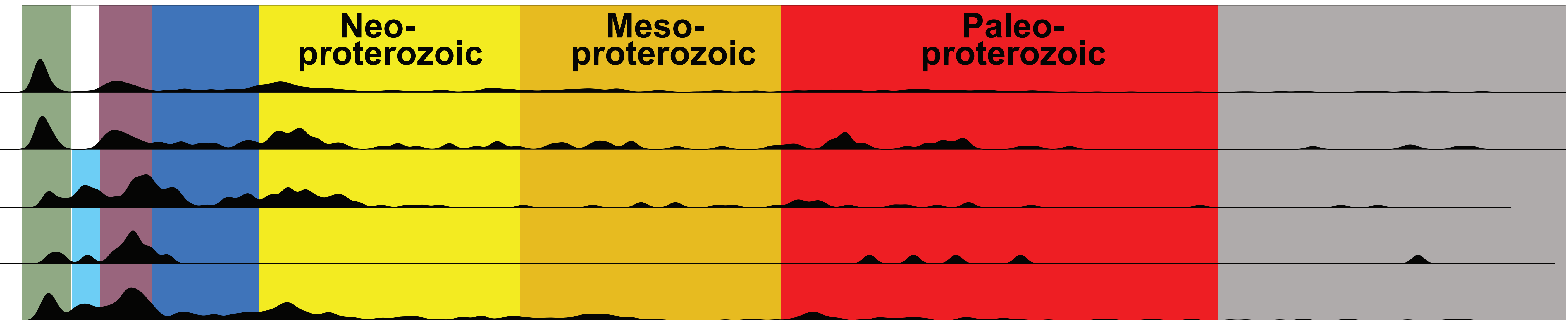


## Banda Arc



1       1       **PROVENANCE OF CRETACEOUS SANDSTONES IN THE BANDA**  
2       2       **ARC AND THEIR TECTONIC SIGNIFICANCE**

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33       14       # Provenance, Palaeogeography, Banda Arc, Tectonic reconstruction, Heavy minerals,  
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## ABSTRACT

The provenance of Cretaceous sandstones in the Banda Arc islands differs from west to east. Sandstones in Sumba and West Timor contain significant amounts of feldspar (K-feldspar and plagioclase) and lithic fragments, suggesting a recycled to magmatic arc origin. In comparison, East Timor and Tanimbar sandstones are quartz rich, and suggest a recycled origin and/or continental affinity. Heavy mineral assemblages in Sumba and West Timor indicate metamorphic and minor acidic igneous sources and include a mixture of rounded and angular zircon and tourmaline grains. In East Timor, Babar and Tanimbar, an ultimate origin from a mainly acid igneous and minor metamorphic source is interpreted, containing a mixture of rounded and angular zircon and tourmaline grains.

Detrital zircon ages in all sandstones range from Archean to Mesozoic, but variations in age populations indicate local differences in source areas. Sumba and West Timor are characterised by zircon age peaks at 80-100 Ma, 200-240 Ma, 550 Ma, 1.2 Ga, 1.5 Ga and 1.8 Ga. East Timor and Tanimbar contain 80-100 Ma, 160-200 Ma, 240-280 Ma, 550 Ma and 1.5 Ga zircon peaks. Most populations are also common in Triassic and Jurassic formations along the Outer Banda Arc and in many other areas of SE Asia. However, the abundance of Jurassic and Cretaceous populations was unexpected. We interpret Cretaceous sandstones from Sumba, Timor and Tanimbar to have been deposited in SE Sundaland. Syn-sedimentary Cretaceous (68-140 Ma) sources are suggested to include the Schwaner Mountains in SW Borneo and Sumba. Material derived mainly from older recycled sediments that had their main sources in the Bird's Head, Western and Central Australia, and local sources close to Timor.

## 1. Introduction

SE Asia is composed of fragments of continental crust, oceanic crust and volcanic arcs, as a result of subduction-related processes in the region, that now form a complex tectonic assemblage (e.g. Hamilton, 1979; Metcalfe, 1998; Hutchison, 1989; Bowin et al., 1980; Hall, 1996, 2011, 2012; Packham, 1996; Charlton, 2001; Hinschberger et al., 2005). Since the Palaeozoic, rifting led to separation of fragments from the Gondwana margin, that were later successively accreted to Sundaland at different times (Fig. 1) (Audley-Charles et al., 1988; Hall, 2012; Barber and Crow, 2009; Metcalfe, 2011, 2013).

During the Mesozoic, large rivers drained the Australian continent and filled the major offshore basins of the NW Shelf, within a fluvial to marginal marine setting (Bishop, 1999; Barber et al., 2003), creating important offshore hydrocarbon reservoirs. The southern Outer Banda Arc islands of Sumba, Timor, Babar and Tanimbar (Fig. 2) are assumed to include the onshore equivalents of these sediments. Mesozoic sandstones have been exposed on these islands due to subduction and collision processes in a complicated tectonic history. Based on heavy minerals and detrital zircon geochronology, Triassic and Jurassic sandstones were interpreted to contain detritus derived from Western and Central Australia, but also an important component previously not recognised, from the Bird's Head region (Fig. 3), and some material from local Jurassic volcanism within the Inner Banda Block (Zimmermann and Hall, 2016).

Late Jurassic rifting of continental slivers from the Australian margin has been described by various researchers (e.g. von Rad et al., 1982; Longley et al., 2002; Heine and Müller, 2005; Hall et al., 2009; Hall, 2012; Heine et al., 2012; Gibbons et al., 2012). Tectonic blocks rifted from areas between the Exmouth

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68 Plateau in the west and the Arafura Sea in the east, where separation of the  
69 continental blocks formed the Banda embayment north of Australia (Hall, 2002,  
70 2012; Charlton, 2012; Spakman and Hall, 2010), and left the Sula Spur (Klompé,  
71 1954) northeast of Australia. The clastic sediments deposited in the Outer Banda Arc  
72 islands before the Late Jurassic rifting were discussed by Zimmermann and Hall  
73 (2016). During the Cretaceous, the Australian-derived continental fragments moved  
74 northwards and were accreted to the Sundaland (Fig. 1) margin (e.g. Audley-  
75 Charles, 1968; Hamilton, 1979; Wensink, 1994; Wakita et al., 1996; Parkinson et al.,  
76 1998; Abdullah et al., 2000; Harris, 2006; Hall et al., 2009; Metcalfe, 2011; Hall,  
77 2012) and clastic sediments were deposited on this continental crust during their  
78 northward movement and after their arrival in SE Asia. During Australia–SE Asia  
79 collision, since the Early Miocene, slices of the SE Asian margin were thrust back  
80 onto the Australian continental margin and are now found in the Outer Banda Arc  
81 islands.

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82 The Cretaceous sandstones discussed in this paper were deposited  
83 after separation of blocks from the Gondwana margin in the Late Jurassic and before  
84 their Neogene thrusting onto the Australian margin in the Outer Banda Arc islands.  
85 Details are still not completely understood and are partly the subject of on-going  
86 research. We present petrology, heavy mineral analyses and U–Pb ages of detrital  
87 zircons from sandstones, siltstones and meta-sandstones. These data help to  
88 identify the origin and possible sources of detrital material and to consider previously  
89 debated tectonic fragmentation in the Banda Arc.



## 2. Post-Triassic Sundaland margin history

The continental blocks rifted in the Late Jurassic were added to Sundaland in the Cretaceous to form what is now much of Borneo, East Java and West Sulawesi. Three principal blocks have been identified (Hall et al., 2009; Metcalfe, 2009; Hall, 2012): the Banda, Argo and Inner Banda blocks, which rifted to leave the oceanic Banda embayment in the northwest Australian margin.

The Banda block was the first to be accreted to the Sundaland margin and is now identified with SW Borneo. For many years SW Borneo was interpreted as a fragment of Asian/Cathaysian origin (e.g. Hutchison, 1989; Metcalfe, 1988, 1990, 1996). The area of the Schwaner Mountains and further south was described as the 'Basement Complex', 'Continental Core' or 'Sunda Shield' (van Bemmelen, 1949) or the West Borneo Basement (Haile, 1974). It was considered to be an ancient continental area, but metamorphic rocks suggested to be Triassic or older (e.g. van Bemmelen, 1949; Haile, 1974; Tate, 1991; Tate and Hon, 1991) were undated and known only to be intruded by Cretaceous granitoids. SW Borneo includes Cretaceous and Jurassic granites in the Schwaner Mountains (Haile et al., 1977; Davies et al., 2014) and the metamorphic rocks are now known to be Cretaceous (Davies et al., 2014). Recent work in Sarawak has identified the boundary of Triassic Sundaland and suggests the Banda/SW Borneo block arrived in the Early Cretaceous at c. 130 Ma (Hennig et al., 2017).

SW Borneo is bounded on its southeast side by the Meratus suture, which can be traced from SW to NE from West Java to the Meratus Mountains of SE Borneo, considered by Hamilton (1979) to be the approximate southeastern boundary of Cretaceous continental crust. The Meratus suture separates SW Borneo from other continental fragments added to the Sundaland margin later in the

115 Cretaceous. In the suture zone in Java and SE Borneo are ophiolitic, arc rocks and  
116 high pressure-low temperature metamorphic rocks which record subduction beneath  
117 Sundaland in the Early Cretaceous. Accretionary-collision complexes in SE Borneo  
118 and Java (Katili, 1971, 1973; Sukanto, 1975a,b; Sikumbang, 1986, 1990; Schiller et  
119 al., 1991; Wakita et al., 1994a,b, 1998; Parkinson et al., 1998; Wakita, 2000;  
120 Clements et al., 2009) include rocks formed by oceanic spreading, arc volcanism,  
121 oceanic and forearc sedimentation, and subduction-related metamorphism. K-Ar  
122 ages from metamorphic rocks summarised by Parkinson et al. (1998) indicate high  
123 pressure-low temperature metamorphism between 117 and 124 Ma, and radiolaria  
124 associated with pillow lavas in Java are Early Cretaceous (Wakita et al., 1994b).  
125 Based on evidence from SE Borneo, Sikumbang (1986, 1990) and Wakita et al.  
126 (1998) concluded that ophiolite emplacement and arc-continent collision was  
127 completed by about 90 Ma.

128                 Several authors (e.g. Luyendyk, 1974; Ricou, 1994; Wakita et al.,  
129 1996; Parkinson et al., 1998; Sribudiyani et al., 2003; van Leeuwen et al., 2007;  
130 Smyth et al., 2007) have suggested that continental fragments accreted to  
131 Sundaland in the Cretaceous, outboard of the Meratus suture, had a Gondwana  
132 origin. The identification of different blocks in Java, SE Borneo and Sulawesi and  
133 interpretation of their former position on the Australian margin are based largely on  
134 zircon age data from different areas.

135                 The Argo block forms the area that now includes much of East Java  
136 and West Sulawesi. Studies in East Java show that the southern part of the island is  
137 underlain by continental crust (Smyth et al., 2007) and suggest that there is similar  
138 crust beneath the Java Sea and in the forearc south of East Java (Deighton et al.,  
139 2011; Granath et al., 2011; Nugraha and Hall, 2012). Inherited zircons in Cenozoic

sedimentary and igneous rocks of East Java range in age from Archean to Cenozoic. The distribution of zircons reveals two different sources. Clastic rocks in north and west parts of East Java contain Cretaceous zircons, which probably came from the Meratus suture or from SW Borneo. In contrast, the Early Cenozoic Southern Mountains volcanic arc of East Java includes abundant acid volcanic and intrusive rocks which contain only Archean to Cambrian zircons. These indicate deep continental Gondwana crust below East Java which originated close to western Australia (Smyth et al., 2007, 2008). Australian-origin continental crust is also considered to underlie parts of the southern Makassar Straits and East Java Sea between Borneo and Java based on basement rocks encountered in exploration wells (e.g. Manur and Barraclough, 1994; Satyana, 2015). Deep seismic data suggest there is similar crust beneath the Java Sea south of Pulau Laut in SE Borneo (Emmet et al., 2009; Granath et al., 2011) and south of East Java (Deighton et al., 2011; Nugraha and Hall, 2012).

Initial reconstructions (Hall et al., 2009; Hall, 2012) of the rifted blocks suggested that the Argo block included all of present-day East Java–West Sulawesi. Hennig et al. (2016) have since shown that zircon age data from NW Sulawesi indicate that the underlying continental crust originated in a position east of the Argo block, and formed part of an Inner Banda block. There are other indications that a single Argo block may be an over-simplification of the deep continental crust east of the Meratus suture, but reconstruction is difficult because basement rocks are limited to small areas and mainly overlain by Cenozoic rocks. Jurassic ammonites and bivalves reported from South Sulawesi (Sukamto et al., 1990; Sukamto and Westermann, 1993) suggest an Australian continental fragment at depth. Elsewhere in western Sulawesi there is evidence from inherited zircons, and from chemical



characteristics of Cenozoic igneous rocks, of underlying continental basement (Priadi et al., 1993, 1994; Bergman et al., 1996; Polvé et al., 1997, 2001; Elburg and Foden, 1999; Elburg et al., 2003). There are blueschists and other high pressure-low temperature metamorphic rocks known from inliers in the Bantimala and Barru areas in South Sulawesi (Sukanto and Supriatna, 1982; Miyazaki et al., 1996, 1998; Parkinson et al., 1998; Maulana et al., 2010, 2013) suggesting sutures between continental blocks. Neogene potassic volcanics in SW Sulawesi do not show the Australian continental isotopic signatures shown by similar volcanic rocks further north in Sulawesi (Elburg et al., 2003) which may indicate an underlying suture. All the supposed suture rocks are very far east of the Meratus suture and cannot be connected to it; they could indicate the Argo block is actually made up of multiple continental fragments separated by sutures or alternatively the observations could be reconciled by postulating the Argo block was hyper-extended continental crust within which were zones of exhumed mantle and deep marine sediments.

The character of the deep crust remains uncertain because there are so few areas exposing rocks older than Cenozoic. Geochemistry and palaeomagnetic studies suggest that Sumba formed part of the Sundaland margin by the Late Cretaceous (Wensink, 1994; Abdullah et al., 2000) but the character of the deep crust is unknown.  $^3\text{He}/^4\text{He}$  ratios suggest that Australian continental crust was involved in genesis of magmas throughout the inner Banda arc from the Banda Ridges to Flores (Hilton et al., 1992). Similar isotope geochemical studies could help identify if the deep crust beneath Sumba is ancient continental or of younger arc origin.

After the arrival of the Argo and Inner Banda blocks, subduction ceased around the Sundaland margin at c.90 Ma. Thus, the outer part of the SE

Sundaland margin was underlain largely by Australian-origin continental crust (Fig. 4). Subsequently, there was a short-lived episode of subduction between the latest Cretaceous and Eocene. Extension in the Eocene formed the Makassar Straits, although the amount of extension in the South Makassar Straits was small (e.g. Situmorang, 1982; Johansen, 2007; Kupecz et al., 2013; Armandita et al., 2015), and there has been major extension of the eastern part of the region which includes Sulawesi and Sumba during Banda rollback from the Middle Miocene (Rigg and Hall, 2012; Camplin and Hall, 2014; Nugraha and Hall, 2018).

### 3. Stratigraphic background

Fig. 2 shows a simplified stratigraphy of the Cretaceous siliciclastic sedimentary rocks investigated (sampling locations in supplementary data file 1).

#### 3.1 Sumba

Upper Cretaceous (Coniacian to Campanian) turbidites of the Lasipu Formation (Fig. 5) in Sumba were described by Burrolet and Salle (1982) and von der Borch et al. (1983). Cretaceous ages were determined by fossil fragments, bivalves, molluscs and gastropods (*Exogyra* sp., *Mytilidae* sp., *Parainoceramus* sp., *Platyceramus* sp. and *Actaeonella* sp.) (von der Borch, 1983). Abdullah et al. (2000) described three magmatic episodes during the Cretaceous to Paleogene, generating pyroclastic rocks, basaltic–andesitic lava flows and granodioritic intrusions.

Rocks collected in Sumba during this study were assigned to the Upper Cretaceous Lasipu Formation. Localities sampled are divided into the central, south-central, western and eastern regions. This newly proposed subdivision highlights

important differences in diagenetic processes and low-grade metamorphism of the  
sediments: the key differences are massive highly indurated metamorphosed rocks,  
with the absence of mudstone in the north, thick siltstone beds interbedded with thin  
mudstone layers in the west, and cyclic siltstone-mudstone interbedded sequences,  
with intercalated sandstone beds in the south and east. A sedimentary log in Fig. 5  
shows an example of the well-bedded siltstone-sandstone intercalations (Fig. 5A) at  
Konda beach in south central Sumba, locally with channel structures (Fig. 5B) and  
layers up to 10-centimetre-thick of medium to coarse-grained sandstone (Fig. 5C).  
13 samples from various locations in Sumba were analysed petrologically, 9 for  
heavy minerals and 7 for zircon geochronology. SUM 06 contains recrystallised Late  
Cretaceous foraminifera (*Globotruncana* sp.) from a shallow inner neritic  
environment (M. BouDagher-Fadel, pers. comm., 2012).

### 3.2 Timor

Timor consists predominantly of Mesozoic sedimentary rocks and  
exotic fragments, that were described as tectonically distributed over the island  
(Audley-Charles, 1986). An important feature is the suggested subdivision of units  
into 1) autochthonous components derived from the Australian continent (lower  
nappes) and 2) allochthonous units of non-Australian origin (upper nappes). These  
have been discussed by many researchers and termed the Banda Allochthon (e.g.  
Audley-Charles & Harris, 1990; Harris, 1991; Audley-Charles, 2011) and commonly  
explained by an alpine-style “overthrust model” (e.g. Carter et al., 1976; Barber,  
1979; Norvick, 1979; Brown and Earle, 1983; Audley-Charles, 1986; Harris, 1989;  
Audley-Charles and Harris, 1990).



Cretaceous sandstones in West Timor belong to the Oe Baat Formation (Sawyer et al., 1993) (Fig. 1) which is a massive calcareous sandstone of grey-green colour (Samples SZ 26, SZ 27 and SZ 47). In East Timor, Cretaceous sandstones have been assigned to the evenly bedded and finely laminated Seical Formation (ET 17). The Seical Formation was not previously recognised at the sampling location, and sandstones there had been interpreted to be Triassic as they resemble rocks of the Babulu Formation in West Timor (Audley-Charles (1968). However, the samples collected contain Late Albian-Early Cenomanian foraminifera (*Hedbergella* sp., *Favusella washitensis*, *Favusella* sp.) from a shallow inner neritic environment (M. Boudagher-Fadel, pers. comm., 2012) and Cretaceous zircons.

### 3.3 Babar

The island of Babar is a typical mud volcano. Before this research no Cretaceous rocks had been reported from Babar. However, in central Babar there is a steep cliff of hard and dense fine-grained siltstone/meta-sandstone with common thick bedding (sample BAB 25). No fossils have been found. The hard and dense meta-sedimentary character of the siltstone closely resembles Cretaceous lithologies seen in Sumba and, like the Lasipu Formation, lithologies were associated with igneous intrusions. As discussed later, detrital zircon ages proved the maximum depositional age of these rocks to be Late Cretaceous.

### 3.4 Tanimbar

Mesozoic sandstones in Tanimbar are exposed on the western islands (Fig. 6A) that are tectonically separated from the main island to the south-southeast

(Kaye, 1989; Charlton et al., 1991). Cretaceous sandstones were assigned to the Ungar Formation and divided informally into two members (Charlton et al., 1991). We recognise the same sandstone members, but include a third intermediate red shale member, which contains radiolarian cherts dated by Jasin and Haile (1996) as uppermost Jurassic to Lower Cretaceous (Zimmermann and Hall, 2016). This member was informally named the Arumit Member (Charlton, pers. comm., 1996, in Jasin and Haile, 1996). The Ungar Formation members are: (1) Lower Sandstone Member, (2) Arumit Member, and (3) Upper Sandstone Member. Neither of the sandstone members has previously been dated. Palynomorphs indicate the Lower Sandstone Member is Upper Jurassic (Zimmermann and Hall, 2016). The Upper Sandstone Member must be Early Cretaceous or younger, based on the work of Jasin and Haile (1996).

The Arumit Member forms an estimated 60m thick clear marker throughout the islands (Fig. 6B). It consists of well-bedded thin red siltstone-mudstone interbeds that dip steeply to the southwest (Fig. 6C and Fig. 6D). Four distinctive chert horizons were recognised within the member and are highlighted in the sedimentary log in Fig. 7. Cherts are between 7 and 15 cm thick and yield radiolaria that were dated by Jasin and Haile (1996). Two horizons were identified as Upper Jurassic (upper Tithonian-Berriasian) and Lower Cretaceous (Valanginian-Barremian) age. The contact of the Arumit Member with the Upper Sandstone Member is indicated in Fig. 6C, which is characterised by mud lenses and imbricated mud clasts within the sandstones.

The Upper Sandstone Member of the Ungar Formation includes fine to medium-grained arkosic sandstones. Rocks are commonly massive bright yellowish-brown. INPEX (pers. comm., 2012) provided comprehensive information for some

sandstones from the islands, based on microfossil analyses (foraminifera, nanoplankton, palynomorphs and radiolaria). The rocks collected for this research were correlated with these previously dated (Upper Jurassic - Lower Cretaceous) samples. 8 samples from various islets were analysed petrologically, 5 for heavy minerals and 4 for zircon geochronology.

## **4. Methodology**

### *4.1 Petrology*

Point counting of at least 300 grains of quartz, feldspar and lithic rock fragments (>0.0625 mm) by standard methods (Galehouse, 1971) was used to acquire light mineral modes, shown on ternary plots for each unit (Dickinson and Suczek, 1979; Dickinson et al., 1983). The fields in the diagrams for QFL (Quartz-Feldspar-Lithics) and QmFLt (Quartz monocrystalline-Feldspar-Lithic total) indicate possible derivation from a 'continental block', 'recycled orogen' or 'magmatic arc'.

Textural categories from 1 to 4 were assigned to qualitatively show sorting and roundness of grains. Sorting categories are (1) poorly sorted, (2) moderately sorted, (3) well sorted and (4) very well sorted. Rounding categories are (1) angular, (2) sub-angular, (3) sub-rounded and (4) rounded.

### *4.2 Heavy Minerals*

Detrital heavy minerals were analysed using standard methods after Mange and Maurer (1992). Samples collected were crushed, decarbonated in 10% acetic acid, sieved and washed (meshes of 0.063mm and 0.250mm) and separated



in a funnel using sodium polytungstate (SPT:  $3\text{Na}_2\text{WO}_4 \cdot 9\text{WO}_3 \cdot \text{H}_2\text{O}$ ) or the lithium equivalent lithium polytungstate (LST), which have densities between 2.82–2.95 g/ml at room temperature. Identification of heavy minerals was performed manually by using an optical polarising microscope (NIKON Eclipse Lv 100) and additional SEM analyses were performed to confirm selected grains. The ribbon count method used was described by Galehouse (1971).

Common heavy minerals were grouped by their most likely protoliths, based on suggested source rock associations (Feo-Codecido, 1956; Mange, 2002; Nichols, 2009). Zircon, tourmaline, anatase, monazite, topaz and xenotime are considered to indicate acid igneous (granitic) sources. Pyroxene (Ortho–OPX and Clino–CPX), titanite (sphene) and chromium spinel represent basic igneous and ultrabasic (commonly arc-related) sources. Rutile, garnet, epidote, andalusite, sillimanite, kyanite, chlorite, staurolite and corundum are interpreted to indicate metamorphic sources, mainly of continental character. Other minerals, such as amphibole, baryte, brookite, zoisite, clinozoisite, sphalerite, prehnite, chloritoid, cassiterite, allanite and vesuvianite are present, either in very low percentages or can be assigned to more than one group. Apatite is a very common mineral and abundant in all samples of this study (up to 50%). Since it can be found in different groups (acid igneous, granite pegmatite, contact metamorphic and basic igneous), it is treated separately.

Varietal studies of zircon (colourless: euhedral, subhedral, subrounded, rounded, anhedral, elongate, zoned; purple: rounded, euhedral; brown, matrix-attached) and tourmaline (brown: rounded, euhedral; blue: rounded, euhedral; green: all shapes) were performed during counting. Three types of grain shapes were recognised: 1) euhedral, subhedral, anhedral, elongated and zoned zircons were

grouped into an 'euhedral' group; 2) rounded and subrounded zircons were grouped into a 'rounded' group; 3) grains with matrix attached represent the third group. Tourmaline grains were classified as either rounded or euhedral.

#### 4.3 Zircon geochronology

Geochronology, using detrital zircons, is a powerful method to assess provenance and correlate sedimentary units (e.g. Goldstein et al., 1997; Cawood et al., 1999, 2003; Fedo et al., 2003; Gehrels et al., 2006; Sevastjanova et al., 2010; Schoene, 2014). The maximum depositional age (MDA) of sedimentary rocks can be determined (Dickinson and Gehrels, 2009) and geochronology is a valuable tool to improve tectonic models and palaeogeographic reconstructions (Murphy et al., 2004).

Selected samples were imaged with scanning electron microscope cathodoluminescence (SEM-CL) at University College London. U-Pb ages were acquired at University College London using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS). U and Pb isotopes were analysed, using the following parameters: spot sizes of the ablation pits: 20-35µm; pulse repetition: 8-10Hz; dwell time: 25s; warm-up: 10-15s; wash-out: 18s. The ablated material was carried in helium gas into the plasma. A quadrupole mass spectrometer (Agilent Technologies 7700 Series ICP-MS) was used. Standards that were used were the Plešovice zircon (337.13±0.37 Ma) by Sláma et al. (2008) and a reference glass NIST SRM 612 (Pearce et al., 1997).

987 selected zircons (Sumba 321, West Timor 133, East Timor 141, Tanimbar 392) were chosen to investigate the relationship of grain shapes and the

analysed ages. The aim was to distinguish optically between rounded grains with recycled histories and euhedral grains, which could have formed close to the time of deposition. A simplified classification scheme was applied, using CL images of the mounted zircons. Morphologies were subdivided into four groups: 1) euhedral; 2) subhedral; 3) subrounded; 4) rounded.

## 5. Results

### 5.1 *Light Minerals: Textures and petrography*

Fig. 8 shows the results of point counting and textural analysis of sandstones from the various islands (tables in supplementary data 2). In general, samples are dominated by quartz, with varying abundances of feldspar and lithic fragments. Sorting and rounding vary between the islands.

13 samples from the Cretaceous Lasipu Formation in **Sumba** were analysed. Grains are angular to subrounded (2-3) and moderately to very well-sorted (2-4). Compositions are dominated by quartz (24-67%), lithic fragments (17-59%) and feldspar (14-26%). However, samples show slight variations of the modal composition between the different areas (Fig. 8). Central and western Sumba are characterised by high volcanic quartz and K-feldspar contents, while south central and eastern Sumba sandstones are dominated by polycrystalline quartz. Samples studied, commonly show a 'recycled orogen' to 'magmatic arc' modal composition on the QFL diagram and a strong magmatic arc origin on the QmFLt diagram (Fig. 8). Textures contain high rounding and sorting values, which plot across the mature field.

In **West Timor** sandstones, the grains are sub-angular and moderately to well sorted. Compositions are dominated by quartz (50-66%), with varying content of feldspar (16-27%) and lithic fragments (18-23%). Quartz types are dominated by polycrystalline quartz (QFL-total: 50% Qp vs 29% Qv vs 21% Qm). As shown in Fig. 8, samples plot in the recycled orogen field on the QFL diagram and within the dissected magmatic arc on the QmFLt diagram. On the textures plot, samples scatter across the immature to mature field boundary (Fig.8).

**East Timor** sandstones contain well sorted (3) sub-angular to rounded (2-4) grains. Marked predominance of quartz (80-89%) is characteristic (Fig. 8). There are also feldspars (5-11%) and lithic fragments (6-9%). The QFL and QmFLt diagrams indicate a 'quartzose recycled orogen' modal composition.

Cretaceous samples from the Upper Sandstone Member of the Ungar Formation in **Tanimbar** are quartz-rich (77-97%) arenites (Fig. 8). Grains are commonly sub-rounded to rounded (3-4) and moderately to very well sorted (2-4). Lithic fragments (max. 9%) and feldspar (max. 14%) are insignificant. Modal compositions plot in the 'recycled orogen'/'continental block' (QFL) to a 'quartzose recycled' (QmFLt) fields. Rounding and sorting indicate a texturally mature polycyclic character (Fig. 8).

## 5.2 Heavy Minerals and their protoliths

Heavy minerals are mainly ultra-stable minerals zircon, tourmaline and rutile, accompanied by apatite, garnet, subordinate andalusite and minor chlorite (tables in supplementary files 3). Fig. 9 summarises heavy mineral assemblages, protoliths and zircon and tourmaline morphology types.

The Lasipu Formation in **Sumba** has a significant metamorphic signal (39-82%) that reflects the abundance of mainly garnet and andalusite (Fig. 9). Sandstones contain on average 14% acid igneous and 2% basic igneous grains. There is a mixture of rounded (17-67%) and euhedral zircon grains (12-48%). An average of 36% of zircon grains are attached to a matrix. Tourmaline is generally less abundant, but dominated by euhedral grains.

The **West Timor** sandstone contains a metamorphic (38%) and acidic igneous (29%) signal indicated by chlorite and zircon (Fig. 9). Zircon grains are a mixture of rounded (48%), euhedral (25%) and attached to matrix (27%).

The **East Timor** sandstone is dominated by grains from an acidic igneous protolith (49%), based on zircon and tourmaline, and a metamorphic source (33%) mainly based on rutile and andalusite (Fig. 9). Zircon grains are mainly rounded (~65%) and tourmalines are dominated by euhedral grain shapes (~74%).

The **Babar** sandstone does not contain a significant amount of ultra-stable heavy minerals. The strong metamorphic signal (Fig. 9) is based on chlorite which represents 81% of the sample.

**Tanimbar** sandstones consist on average of 52% acid igneous grains (mainly zircon and tourmaline). 32% metamorphic sources are mainly based on rutile, andalusite and garnet. Morphologies of zircons are dominantly euhedral (42-66%) and rounded (34-54%). Tourmalines on average are 57% euhedral and 43% rounded.

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### 5.3 Zircon Geochronology

The numerical ages assigned here to periods, epochs and stages are based on Gradstein et al. (2012). Data tables of LA-ICP-MS analyses are provided in the supplementary data 4, which contains  $^{207}\text{Pb}/^{235}\text{U}$  ratios,  $^{206}\text{Pb}/^{238}\text{U}$  ratios, calculated ages and preferred ages, considering exclusion of discordant grains. Histograms of detrital zircon ages and according grain morphologies of Cretaceous sandstones in the Banda Arc show generally a mixture of different age populations (Fig. 10), with similar proportions of Precambrian to Phanerozoic grains.

In **Sumba** 583 concordant LA-ICP-MS U-Pb detrital zircon ages were obtained from samples SUM 1, SUM 6, SUM 10, SUM 21, SUM 22, SUM 24 and SUM 30. The youngest zircon ages ( $71.9\pm 1$  Ma in SUM 6 to  $84.7\pm 1.6$  Ma in SUM 10) constrain the maximum depositional age (MDA) as Campanian to Maastrichtian (mean age of three youngest overlapping zircon ages 69.3 Ma). Samples contain zircons with 48.5% Phanerozoic, 47.9% Proterozoic and 3.6% Archean ages. Most abundant age populations (Fig. 10A) are Neoproterozoic (20.6%), Cretaceous (19.9%) and Mesoproterozoic (14.9%). The main peaks are at 80-100, 230, 550, 1200 and 1600 Ma. Zircon grain morphologies of Cretaceous grains are dominated by euhedral and subhedral grains, Permian-Triassic zircons are euhedral and subhedral, Cambrian to Carboniferous zircons are subhedral to subrounded and Precambrian grains are mainly subrounded and rounded (Fig. 10B).

Sample SZ 47 from **West Timor** was sampled at a location mapped as the Oe Baat Formation which has a Tithonian to Berriasian age (Charlton, 1987; Sawyer et al., 1993). It contains 132 concordant zircon ages. However, the sample contains 16 Cretaceous grains and the youngest zircon age ( $75.5\pm 1.4$  Ma) indicates

a Campanian (Late Cretaceous) MDA, which means that it cannot be part of the Oe Baat Formation. This shows the value of the detrital zircon ages which indicate that a sandstone mapped previously as an older formation belongs to a different, so far unnamed, formation. SZ 47 contains 40.9% Phanerozoic, 55.3% Proterozoic, and 3.8% Archean ages. There are no Jurassic grains. The most abundant age populations are Neoproterozoic (22.7%), Paleoproterozoic (16.7%) and Mesoproterozoic (15.9%). The main peaks are at 85, 220-240, 550 and 1600 Ma (Fig. 10A). Zircon grains with Cretaceous ages are dominated by euhedral and subhedral grains. Paleozoic zircons show a mix of subrounded/rounded and euhedral/subhedral grain morphologies. Proterozoic zircons are mainly rounded and subrounded (Fig. 10B). It is not clear to which formation this sandstone should be assigned, but, there are clearly Cretaceous or younger sandstones in southern West Timor. Sample SZ 37 was collected in the Kolbano area and also mapped as the Oe Baat Formation and contains belemnites supporting this assignment. However, it contains a single Cretaceous zircon, with one Permian grain, and abundant Proterozoic zircons, but also contains Eocene foraminifera (M. BouDagher-Fadel, pers. comm., 2015). The belemnites must therefore be reworked. The Eocene rocks in Kolbano were all previously assumed to be carbonates only and clearly need remapping (A.J. Barber, pers. comm., 2018).

ET 17 in **East Timor** provided 144 concordant analyses. The youngest zircon age ( $97.3 \pm 1.3$  Ma) constrains the MDA to the Late Cretaceous (Cenomanian). Zircon populations include 58.9% Phanerozoic, 39.7% Proterozoic and 1.4% Archean ages. The most abundant age populations are Cambrian to Carboniferous (23.6%), Neoproterozoic (22.2%) and Permo-Triassic (18.8%). There is a small population of Cretaceous zircons (6.9%) and a greater number of Jurassic grains

(10.4%) The main peaks are at 95, 170, 260, 280 and 550 Ma (Fig. 10A). There is no 1800 Ma peak. It is striking that most zircons have subhedral and euhedral grain morphologies for most populations. The predominance of euhedral and subhedral grains for Cretaceous, Jurassic, Permo-Triassic and Cambrian-Carboniferous suggests little recycling of most zircons (Fig. 10B).

No Cretaceous rocks have previously been described from **Babar**. As mentioned earlier, sandstones are unfossiliferous and undated. The youngest zircon ( $104.7 \pm 1$  Ma) in sample BAB 25 from Babar indicates an Early Cretaceous (Albian) MDA. Sample BAB 25 yielded only 17 concordant analyses and the ages must be interpreted with care as some populations are likely to have been missed but the ages are comparable to populations in Cretaceous sandstones from Tanimbar and East Timor (Fig. 10A). The sample consists of 70.6% Phanerozoic, 23.5% Proterozoic and 5.9% Archean ages. Most abundant ages are Permo-Triassic (41.2%), Paleoproterozoic (23.5%) and Cretaceous (11.8%).

Cretaceous samples from **Tanimbar** belong to the Upper Sandstone Member of the Ungar Formation. Charlton et al. (2009) suggested an Early Cretaceous age which is supported by palynomorph analyses (INPEX, pers. comm., 2012). Combined Cretaceous samples yielded 429 concordant analyses from samples TAN 11 (MDA  $84.6 \pm 1$  Ma), TAN 28 (MDA  $83.7 \pm 1$  Ma), TAN 31 ( $89.5 \pm 1$  Ma) and TAN 45 ( $103.6 \pm 2$  Ma). The youngest zircon ages within this group indicate an MDA of Santonian (Late Cretaceous), and an age range of Santonian to Albian, which is younger than previously suggested. Cretaceous samples contain zircons of 54.3% Phanerozoic, 43.8% Proterozoic and 1.9% Archean ages. The most abundant age populations are Permo-Triassic (21.2%), Neoproterozoic (20.3%) and Cambrian to Carboniferous (15.6%). Important Cretaceous (10.3%) and Jurassic (~8%)



populations are also present. The main peaks are at 100, 150-170, 240-280, 550, 1200 and 1800 Ma (Fig. 10A). It is striking that most zircons show subhedral and euhedral grain morphologies for Mesozoic and Paleozoic populations (Fig. 10B).

## 6. Discussion

Quartz-rich sandstones from Sumba, West Timor, East Timor, Babar and Tanimbar vary in light and heavy mineral compositions, which generally indicate mixed sources (Fig. 8). Slight differences in the modal compositions and textural analyses suggest derivation from a magmatic arc for Sumba and West Timor (immature to mature character with a mix of euhedral and rounded grains) and a recycled orogen for East Timor and Tanimbar, where morphologies are predominantly rounded.

Heavy mineral compositions are dominated by high concentrations of metamorphic minerals (mainly garnet and andalusite) in Sumba and West Timor (Fig. 9). In contrast, East Timor and Tanimbar contain high abundances of rounded zircon and tourmaline which supports the multiply recycled sedimentary character of grains from an acidic igneous source.

Zircon populations in Cretaceous sandstones of the Banda Arc islands resemble each other (Fig. 10). All islands contain Cretaceous zircons that are predominantly euhedral and subhedral, which suggests nearby volcanic sources at the time of deposition. The general distribution of age populations and corresponding grain morphologies suggest a mixture of different sources. However, differences between Sumba–West Timor (SWT) and Tanimbar–East Timor (TET) are noteworthy. SWT shows common Paleoproterozoic (1.5-1.8 Ga), Mesoproterozoic

(1.2 Ga) and Neoproterozoic (500-650 Ma) peaks, but in TET the 1.8 Ga population is significantly lower. The most striking feature in TET is the abundance of Jurassic zircons that are missing in SWT and in Jurassic sandstones, such as the Lower Sandstone Member of the Ungar Formation, shown in Fig. 11 (from Zimmermann and Hall, 2016). The 550 Ma peak is present in all Cretaceous samples, but missing in most Triassic and Jurassic formations. The Cretaceous sandstone from Babar yielded only 17 concordant grains, including 2 Cretaceous ages. Lithologically it resembles the Sumba Lasipu Formation, but the small number of zircons includes a Jurassic grain, and this sample therefore resembles East Timor and Tanimbar sandstones more closely rather than those from Sumba and West Timor. Furthermore, there are abundant Permian-Triassic and Cambrian to Carboniferous populations in TET, but grains of this age are of minor significance in SWT (Fig. 10 and Fig. 11).

## 6.1 Possible Sources

Fig. 12 shows zircon age histograms for SE Asian units that contain Cretaceous and Jurassic zircons, such as the Schwaner Mountains in Borneo (Davies et al., 2014) and Central Sulawesi, including inherited ages from metamorphic and S-type granitoids (Hennig et al., 2016). In contrast, autochthonous Cretaceous deposits that remained in Australia, such as well samples from the Exmouth Plateau and Caswell Plateau (Southgate et al., 2011; Lewis and Sircombe, 2013), do not contain any, or very few, Phanerozoic zircons.

### 6.1.1 *Pre-Breakup sources*

Provenance and geochronology studies of Triassic and Jurassic sandstones from autochthonous formations in the Banda Arc, shown in Fig. 11 (Zimmermann and Hall, 2016), together with studies along the Australian NW Shelf (Southgate et al., 2011; Lewis and Sircombe, 2013) (Fig. 12), the Bird's Head (Gunawan et al., 2012) and Central Sulawesi (Hennig et al., 2016) are a useful guide to linking sandstones to likely sources in Western Australia, Central Australia and the Bird's Head region (Fig. 13).

### 6.1.2 *Post-Breakup sources*

Continental fragments rifted from the northern Australian continent in the Late Jurassic (Fig. 3). Collision of these allochthonous fragments in the Cretaceous added the Argo, Banda and Inner Banda Blocks to the Sundaland margin (Fig. 4). After their arrival, the siliciclastic sediments deposited had sources in SE Asia including igneous rocks and reworked older crust. Australian material (igneous, metamorphic and sedimentary) that had been transported with the fragments and included inherited Precambrian zircons from continental crust with a west Australian origin (e.g. beneath East Java), as reported by Smyth et al. (2007, 2008) and Hall et al. (2009). Jurassic volcanic activity was suggested by Zimmermann and Hall (2016), based on zircons in West Timor sandstones, with a source along the NW Shelf of Australia within the southern Banda Block–Inner Banda Block (Hennig et al., 2016). Volcanic activity was driven by the break-up of Gondwana and the subsequent fragmentation and drift of continental Australian blocks.

The most common Cretaceous age peaks in this study are different in SWT and TET; they are c. 90-80 Ma in Sumba and West Timor (SWT), and c. 110-90 Ma (minor 130 Ma) in East Timor, Babar and Tanimbar (TET). Gunawan et al. (2012) interpreted Late Cretaceous ages from the Sirga Formation (c. 88 Ma) in the Bird's Head as most likely to have been derived from a local source. Abundant granites of Cretaceous age in the Borneo Schwaner Mountains (Banda Block) were interpreted as having been derived from pulses of magmatic activity around 112, 98, 84 and 76 Ma (Davies et al., 2014). Common populations in the granitoids are 120-100 Ma and 90-80 Ma. In contrast, Cretaceous granodiorite intrusions from Sumba are younger and were dated at 86-77 Ma and 71-56 Ma (Abdullah et al., 2000).

Fig. 13 shows a map that is based on previous studies in greater Australia and SE Asia, highlighting the islands investigated and possible main regions (i.e. granitoid bodies, cratons and fragments) that could have supplied material to the Banda region.

## 6.2 Provenance of Cretaceous sandstones in the Banda Arc

The Schwaner Mountains in Borneo (granites generally older than c. 86 Ma) and granodiorite intrusions from Sumba (younger than c. 86 Ma) are the most probable sources of contemporaneous Cretaceous zircons (Fig. 10 and Fig. 12). However, older zircons must have come from other places since pre-Cretaceous zircons are absent in the north Schwaner Mountains, although a few Jurassic granites are known from the south Schwaner Mountains, and pre-Cretaceous rocks are not known from Sumba. Significant Archean, Neo and Meso-Proterozoic

populations show similarities to autochthonous Triassic-Jurassic and Cretaceous sandstones in the Banda Arc (Fig. 11) and the Australian NW Shelf (Fig. 12). These were mainly derived from Western and North/Central Australia and the Bird's Head. This also explains abundant Permian-Triassic and Cambrian to Carboniferous populations in TET and SWT. Cretaceous zircons are missing in the autochthonous Australian units and support a SE Asian setting for the Banda Arc Cretaceous sandstones that form part of the Banda Allochthon (BA) or Banda Terrane (Audley-Charles, 2011) for the individual islands: BA West Timor, BA East Timor, BA Babar and BA Tanimbar.

In order to estimate the possible contribution of different sources, a cumulative percentage plot in Fig. 14A highlights relative abundances of ages and probable sources. TET contains abundant Jurassic zircons that are missing in SWT and in Jurassic sediments within the Argo Block (e.g. origin of the Lower Sandstone Member of the Ungar Formation in Fig. 11). Hence, a geographical separation with different provenance is necessary (Fig. 14B). The ultimate Jurassic source was probably located within the Banda Block/Inner Banda Block.

A Cretaceous palaeogeographic reconstruction with major sediment transport directions (Fig. 14B) shows suggested sources for Cretaceous formations in the Banda Arc that are now part of the Banda Allochthon, including West Timor (BA-WT), East Timor (BA-ET), Babar (BA-B), and Tanimbar (BA-T). The heavy mineral and zircon age data suggest a syn-sedimentary Cretaceous source in the Schwaner Mountains and Sumba, together with recycling of Permian-Triassic and Jurassic pre-rift units.

Data from the Northwest Shelf of Australia (Southgate et al., 2011; Lewis and Sircombe, 2013), Java (Smyth et al., 2003, 2007), Borneo (Davies et al.,

2014) and Sulawesi (Hennig et al., 2016) were included (Fig. 14A) to highlight age similarities and assess possible reconstructions. Trends can be recognized by decreasing or increasing percentages of single zircon populations. Ultimate main sources for the Banda Allochthon sandstones are a mix of Cretaceous populations derived from Sundaland (Schwaner Mountains) and zircons derived from pre-Cretaceous rocks formed, or deposited before separation from greater Australia. Single grain morphologies of zircons analysed (Fig. 10B) support interpretations of contemporaneous first cycle Cretaceous grains and a Permian-Triassic signal. Rounded Proterozoic (Australian) grains are also mixed with subhedral grains indicating differences in recycling of Australian cratons.

In **Sumba**, the principal zircon populations indicate sources in Western Australia (33%), North/Central Australia (26%), Borneo/Sumba (24%) and the Bird's Head region (16%) (Fig. 14A). 57% of Cretaceous zircons have ages less than c. 86 Ma, indicating a relationship to the Sumba granodiorites and/or the later eruptive stages of the Schwaner Mountains. Based on previous research (Sallé, 1982; von der Borch et al., 1983) and new field observations the rocks are interpreted as turbidites deposited in deep water. The variation in rocks in the central part of the island and around the south and southwest coast suggest facies changes along the shelf and slope. **West Timor** (BA-WT) contains similar population percentages as Sumba, mainly from Western Australia (36%), North/Central Australia (33%), Borneo/Sumba (12%) and the Bird's Head (19%) (Fig. 14A). 31% of the Cretaceous population are younger than 86 Ma indicating input from Sumba granodiorites and/or the later eruptive stages of the Schwaner Mountains.

**East Timor** (BA-ET) is sourced by Western Australia (35%), the Bird's Head (31%), North/Central Australia (17%), the Banda Block (10%) and Borneo

(7%), of which >100 Ma old zircons dominate (80%), indicating a probable source in the Schwaner Mountains, whereas younger (<86 Ma) Sumba ages are absent.

In **Tanimbar** (BA-T), the main sources are similar to East Timor, deriving from Western Australia (31%), the Bird's Head (28%), North/Central Australia (23%), the Banda Block (8%) and Borneo (10%) (Fig. 14A). The Cretaceous population is strongly dominated by >86 Ma zircons (95%), indicating a likely source in the Schwaner Mountains with very minor possible contribution from Sumba. Thus, we suggest that sediment was transported to the site of deposition mainly from the west but also from the east (Fig. 14B).

As noted before, one Cretaceous sample from **Babar** (BA-B) yields only 17 concordant U-Pb zircon ages and it is not likely that such a small number of grains provides a representative sample. However, the few ages do suggest possible provenance trends. The main features are similarities to Cretaceous samples from East Timor and Tanimbar, suggesting the geographical location of the BA-B fragment was where it is now, between BA-ET and BA-T (Fig. 14B).

### 6.3 *Tectonic Evolution of the Banda Allochthon*

Previous researchers (e.g. Wensink, 1994; Abdullah et al., 2000; Hall et al., 2009; Hall, 2012; Metcalfe, 2013) proposed models with fragments derived from Australia colliding with Sundaland. Modifications of previous palaeogeographic and tectonic reconstructions (Hall, 2012) are suggested here to locations of individual fragments and evolution of sediment supply, following Triassic and Jurassic reconstructions by Zimmermann and Hall (2016). Fig. 15A displays the rifting of fragments (Argo, Banda and Inner Banda) from the Early Cretaceous (130

Ma) and the situation within the Sundaland margin in the Late Cretaceous (75 Ma). The figures show the drift history to the north and collision with Sundaland with interpreted locations of the Banda Allochthon fragments in the Sundaland margin at 75 Ma. Sumba and BA-WT (SWT) are situated at the southern edge of Sundaland and were supplied by sediment from the north (Borneo) and east by local erosion of the Argo Block. BA-ET, BA-B and BA-T (TET) were situated at the eastern margin. Sediment was mainly derived from the east (Borneo and West Sulawesi) and from the north (reworking of the southern edge of the inner Banda Block).

Interpreted Cenozoic movements to the present-day locations of different fragments are shown in Fig. 15B. At around 23 Ma, the most northerly part of Australia (Sula Spur) collided with Sundaland, followed by subduction hinge rollback into the Banda Embayment (Spakman and Hall, 2010) and initial fragmentation of the Sula Spur (from c. 15 Ma).

The 5 Ma palaeogeographic map shows the setting shortly before the collision of the Banda volcanic arc with the Australian continent and the resulting emplacement of the Banda Allochthon. The present-day configuration was reached by overthrusting of these units on top of Mesozoic and pre-Triassic autochthonous (Gondwanan) sediments and basement, coupled with rapid uplift that created the Outer Banda Arc Islands.

## **7. Conclusions**

Earlier studies of the Northwest Shelf of Australia identified sources for Permian-Triassic and Jurassic sandstones in Central and Western Australia and the Bird's Head, depositing the pre-breakup sequence. From the Late Jurassic, rifting of



the Australian Gondwana margin caused fragmentation and separation into blocks which were accreted to Sundaland in the Early and Late Cretaceous.

Cretaceous sandstones were deposited unconformably on top of the pre-breakup sequence at the southeastern margin of Sundaland in what was to become the Banda Allochthon. The sandstones commonly contain significant contents of volcanic quartz, feldspar and lithic fragments, indicating mixed sources for the fragments that later became Sumba, BA-West Timor, BA-East Timor, BA-Babar and BA-Tanimbar. The principal source rocks are suggested to be of metamorphic origin in Sumba and West Timor (SWT), and acidic igneous and recycled sedimentary rocks in East Timor and Tanimbar (TET). Contemporaneous Cretaceous igneous sources include Sumba and the Schwaner Mountains within Sundaland. Variations between the SWT and TET fragments suggest differences in provenance, most likely due to geographical separation along the southern shelf of Sundaland. Neogene extension further isolated these Cretaceous sandstones and Neogene collision processes moved these fragments into the Outer Banda Arc Islands, where they are overthrust and now re-incorporated in the Australia margin.

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## **Appendix A. Supplementary data**

Supplementary data to this article can be found online. Supplementary Data File 1 contains data tables of sampling locations, formations and lithologies. Supplementary Data File 2 contains data tables of modal compositions and textural analyses. Supplementary Data File 3 contains data tables of heavy mineral analyses. Supplementary Data File 4 contains data tables of LA-ICP-MS analyses.

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## Figure Captions

Fig. 1: Simplified map of SE Asia showing the Banda Arc Islands and blocks that rifted from Gondwana and were added by accretion to Sundaland (modified from Hall and Sevastjanova, 2012).

Fig. 2: The Banda Arc Islands discussed in this paper: Sumba, Timor, Babar and Tanimbar, showing key features of the stratigraphy of each island and the Mesozoic formations (Fm=Formation) that were analysed, with sample locations. Deep marine samples are highlighted in yellow and shallow marine samples in blue.

Fig. 3: Pre-breakup reconstruction in the Triassic showing the principal blocks rifted in the Jurassic with interpreted major sediment transport directions and suggested sources (from Zimmermann and Hall, 2016). Dark coloured areas are potential sources of zircon age populations.

Fig. 4: Reconstruction of Sundaland margin in the Cretaceous at c. 90 Ma after accretion of continental blocks rifted from the Banda embayment, based on Smyth et al. (2007), Hall et al. (2009), Hall (2012), and Hennig et al. (2016). The Banda block is present-day SW Borneo, the Argo block includes East Java and parts of West Sulawesi, and the Inner Banda block includes NW Sulawesi, and parts of NE Borneo.

Fig. 5: Sedimentary log of the well-bedded siltstone-sandstone intercalations at Konda Beach in south central Sumba; A) Interbedded sandstones and siltstones with up to 5 centimetres thick sandstone layers and internal fining upwards units; B) Small channel in siltstone sequence; C) Layer of a 10 centimetres thick medium to coarse-grained sandstone.

Fig. 6: A) Simplified geological map of the Tanimbar Islands, based on data collected in the field and structural interpretations modified from Kaye (1989); B) Panoramic view of the Arunit Member on Ungar Island; C) Well-bedded interbedded siltstones and mudstones; D) Contact of red shales of the Arunit Member with the Upper Sandstone Member.

Fig. 7: Sedimentary log of the Arunit Member of the Ungar Formation, showing details of the succession on Ungar Island and its interpreted relationship to the



Lower and Upper Sandstone Members. Chert layers are highlighted in red and radiolarian ages are based on Jasin and Haile (1996).

Fig. 8: Summary of light mineral point counting of Cretaceous sandstones from the various islands. Ternary plots after Dickinson et al. (1983) showing possible provenance affiliation (Q – Quartz, F – Feldspar, L – Lithic fragments, Qm – Monocrystalline quartz, Lt – Total lithic fragments). Textures show assessments of sorting and rounding using simple number schemes which were used to estimate maturity.

Fig. 9: Summary plots of heavy mineral percentages, interpreted protoliths and varietal morphology of Cretaceous sandstones from the various islands.

Fig. 10: Histograms showing grouped zircon ages for Cretaceous formations from islands in the Banda Arc with possible sources. Bin width on the left (0-500 Ma) is 10 Ma, on the right (500-4000 Ma) is 50 Ma. Total numbers of zircons for each group are highlighted (red indicates the greater numbers, green the smaller). Percentages of Precambrian zircon grains that are older than 541 Ma are indicated; B) Bar charts for samples grouped according to age showing zircon morphology types for different age groups (Cr = Cretaceous, J = Jurassic, P/T = Permian-Triassic, C/C = Cambrian–Carboniferous, Neo = Neoproterozoic, Meso = Mesoproterozoic, Paleo = Paleoproterozoic, Arch = Archean).

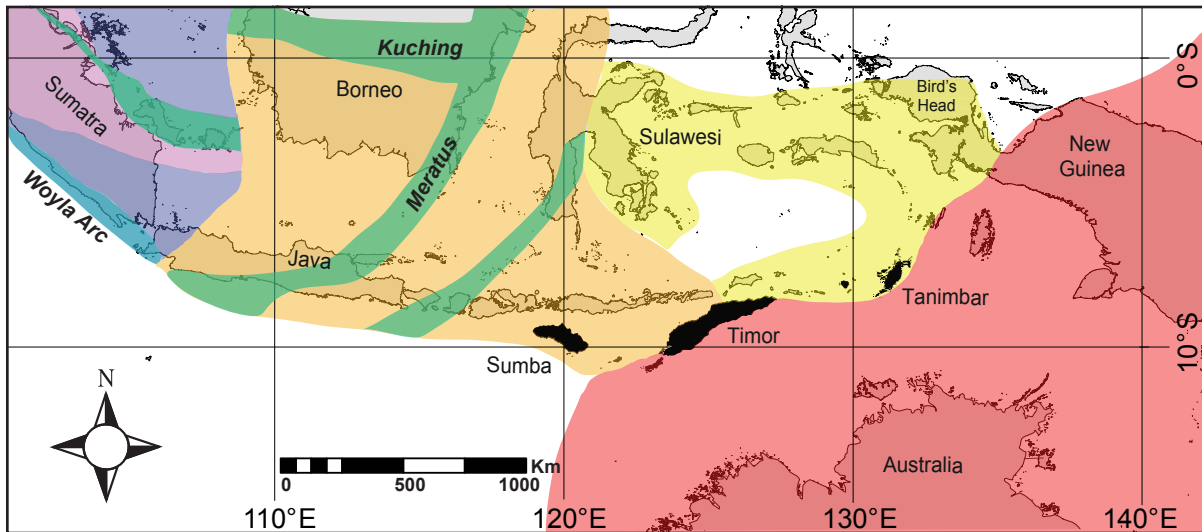
Fig. 11: Kernel density estimation plots of Cretaceous formations from this study compared to Triassic and Jurassic formations from Zimmermann and Hall (2016). Colours indicate individual population ages (Cr=Cretaceous, J=Jurassic, P-T=Permian-Triassic, C-C=Ordovician-Carboniferous).

Fig. 12: Histograms summarizing the main features of zircon ages for the Schwaner Mountains of Borneo, Central Sulawesi and offshore Australia with colour bands marking likely sources. Bin width on the left (0-500 Ma) is 10 Ma, on the right (500-4000 Ma) is 50 Ma. Total numbers of zircons for each group are highlighted (red indicates the greater numbers, green the smaller). Percentages of Precambrian zircon grains that are older than 541 Ma are indicated.

Fig. 13: Map showing possible source areas in Australia and SE Asia with ages that resemble age populations found in the Banda Arc Islands and the NW Shelf of Australia (modified from Zimmermann and Hall, 2016).

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Fig. 15: A) Tectonic reconstructions for SE Asia (based on Hall, 2012) with focus on the rifting Argo and Banda terranes from the Late Jurassic to Early Cretaceous; B) Tectonic reconstructions of the Banda Allochthon (BA) at 23 Ma showing the initial collision between the Sula Spur and Sundaland; at 15 Ma showing subduction hinge rollback and early stage of fragmentation of the Sula Spur; at 5 Ma showing location of allochthonous fragments before Timor arc-continent collision; and present-day configuration highlighting the outer Banda Arc Islands with overthrust fragments.



Time of rifting from Gondwana:

- Devonian
- Early Permian
- Late Jurassic

Volcanic arc accreted in the Cretaceous

Greater Australia:

- Fragmented Sula Spur
- Australian margin

- Suture Zone
- Research Area

**Fig. 1:** Simplified map of SE Asia showing the Banda Arc Islands and blocks that rifted from Gondwana and have been added by accretion to Sundaland (modified from Hall and Sevastjanova, 2012).

Figure 2

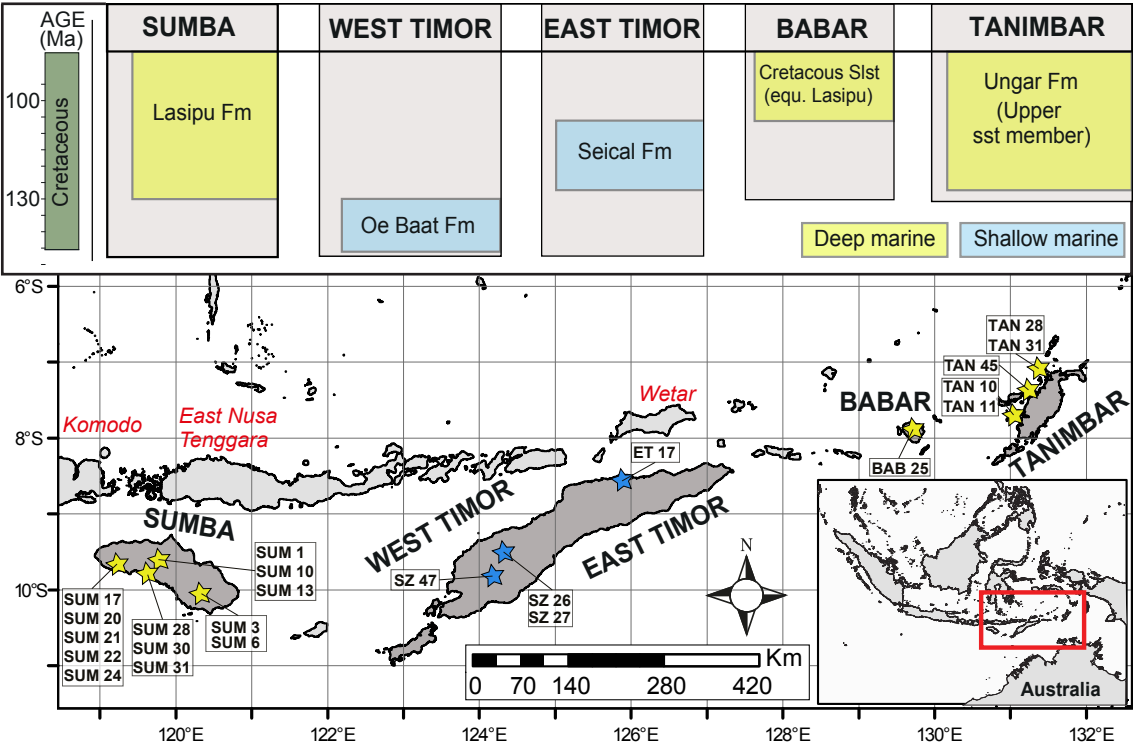


Fig. 2: The Banda Arc Islands discussed in this paper: Sumba, Timor, Babar and Tanimbar, showing key features of the stratigraphy of each island and the Mesozoic formations (Fm=Formation) that were analysed, with sample locations. Deep marine samples are highlighted in yellow and shallow marine samples in blue.

Figure 3

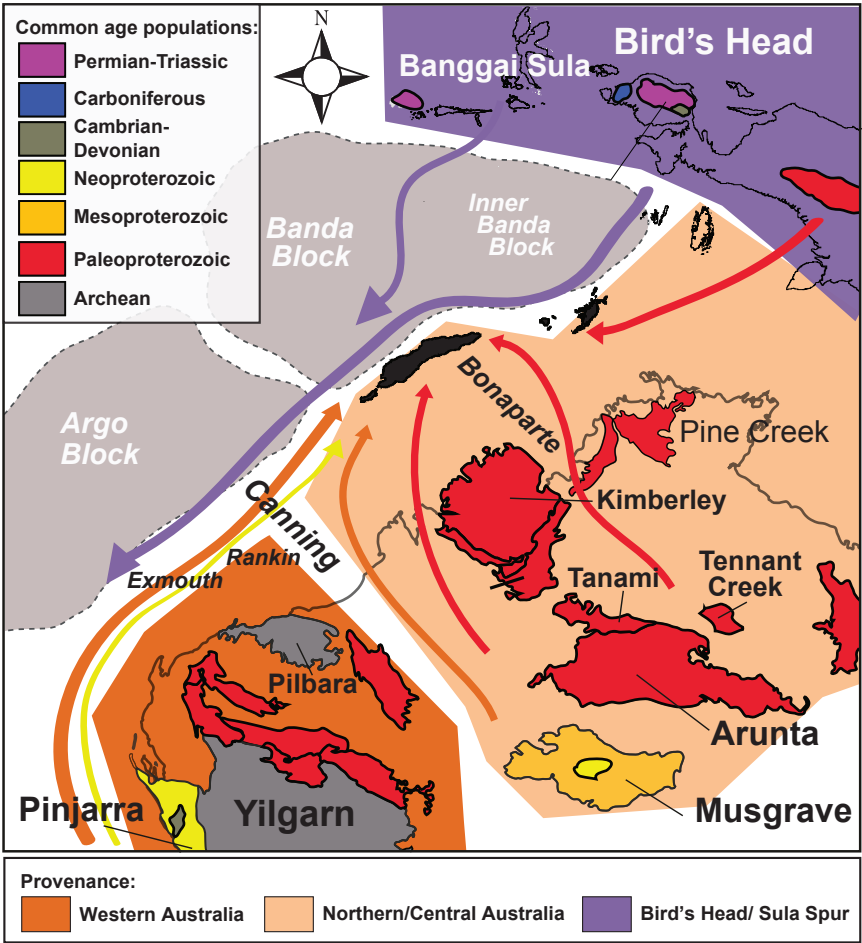


Fig. 3: Pre-breakup reconstruction in the Triassic showing the principal blocks rifted in the Jurassic with interpreted major sediment transport directions and suggested sources (from Zimmermann and Hall, 2016). Dark coloured areas are potential sources of zircon age populations.

Figure 4

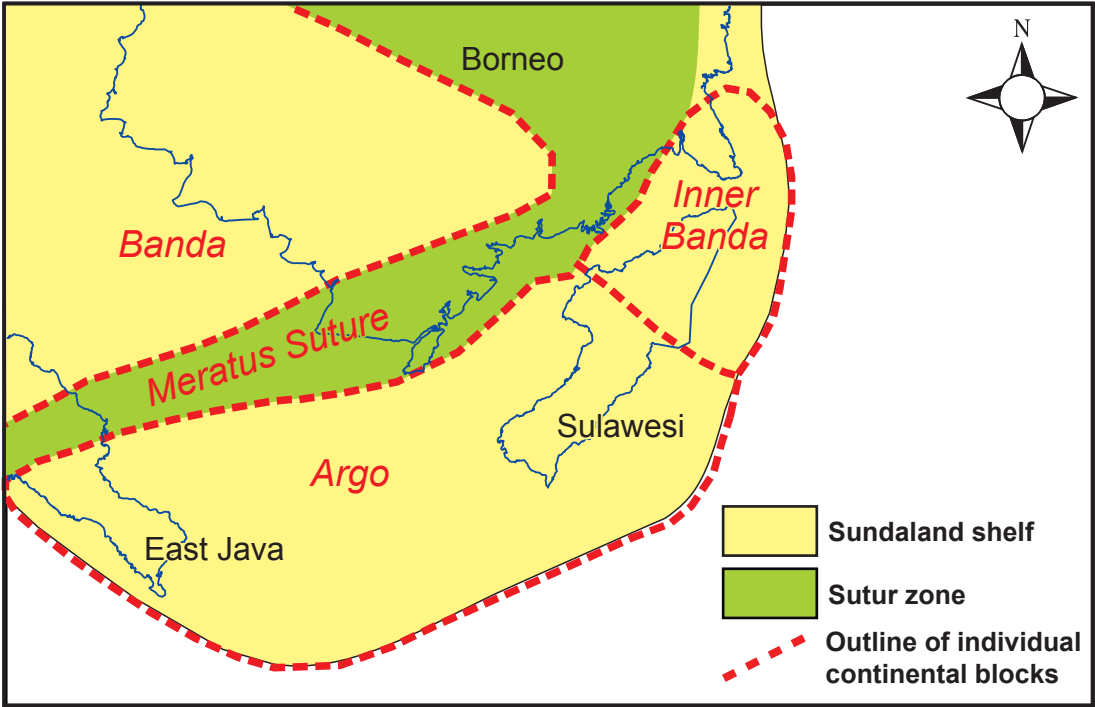


Fig. 4: Reconstruction of Sundaland margin in the Cretaceous at c. 90 Ma after accretion of continental blocks rifted from the Banda embayment, based on Smyth et al. (2007), Hall et al. (2009), Hall (2012), and Hennig et al. (2016). The Banda block is present-day SW Borneo, the Argo block includes East Java and parts of West Sulawesi, and the Inner Banda block includes NW Sulawesi, and parts of NE Borneo.

Figure 5

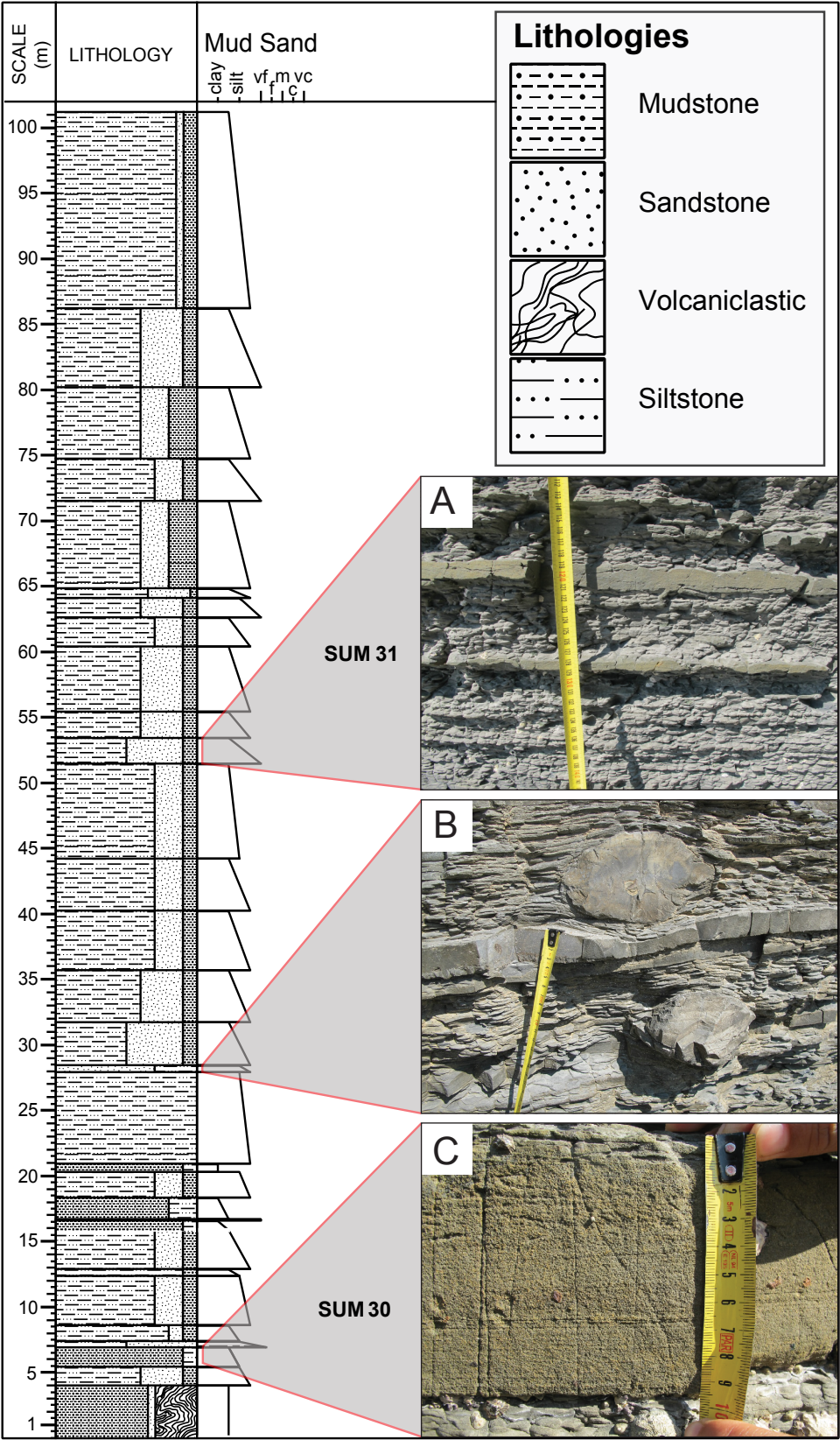


Fig. 5: Sedimentary log of the well-bedded siltstone-sandstone intercalations at Konda Beach in south central Sumba; A) Interbedded sandstones and siltstones with up to 5 centimetres thick sandstone layers and internal fining upwards units; B) Small channel in siltstone sequence; C) Layer of a 10 centimetres thick medium to coarse-grained sandstone.



Figure 6

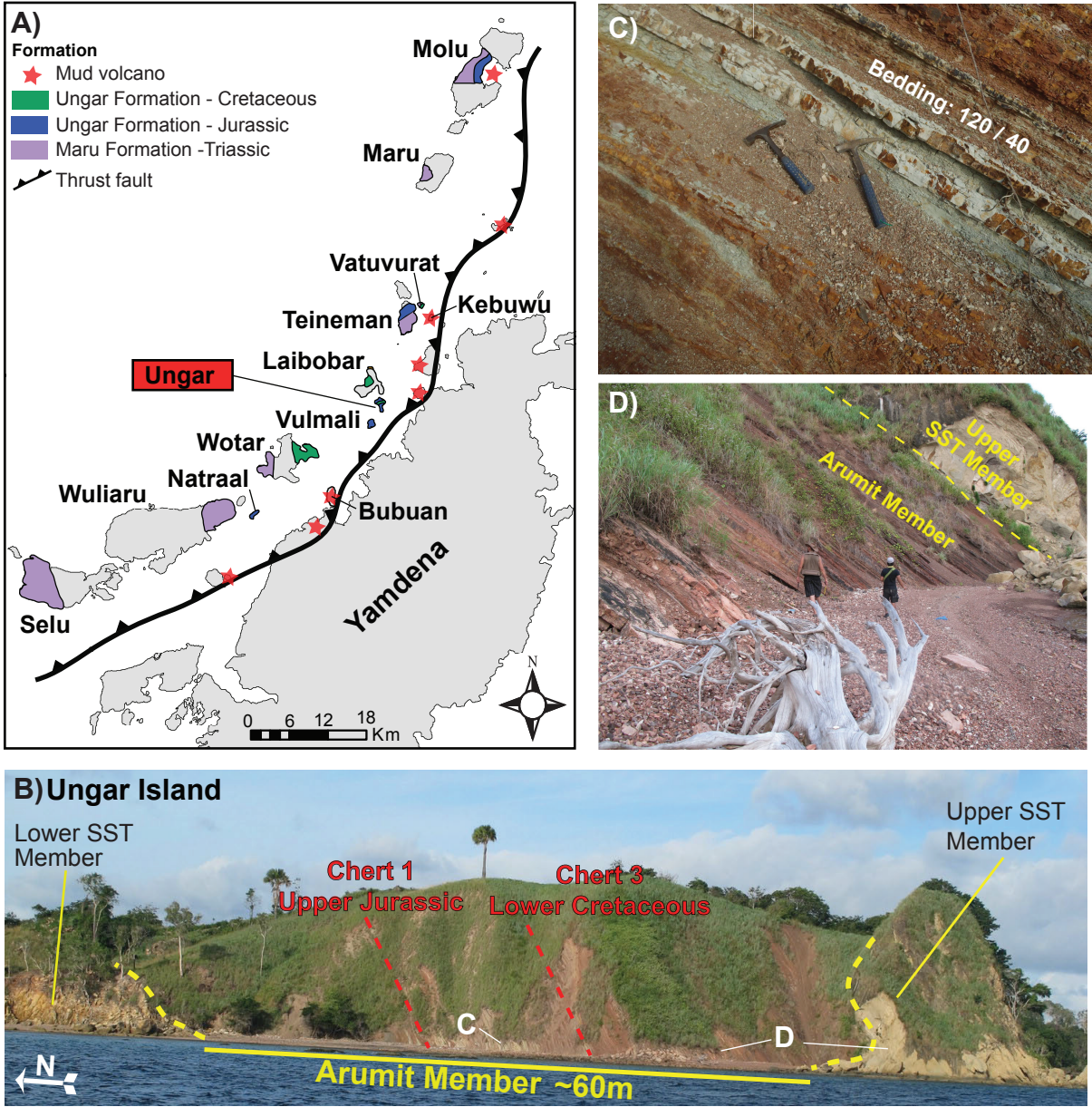


Fig. 6: A) Simplified geological map of the Tanimbar Islands, based on data collected in the field and structural interpretations modified from Kaye (1989); B) Panoramic view of the Arumit Member on Ungar Island; C) Well-bedded interbedded siltstones and mudstones; D) Contact of red shales of the Arumit Member with the Upper Sandstone Member.



Figure 7

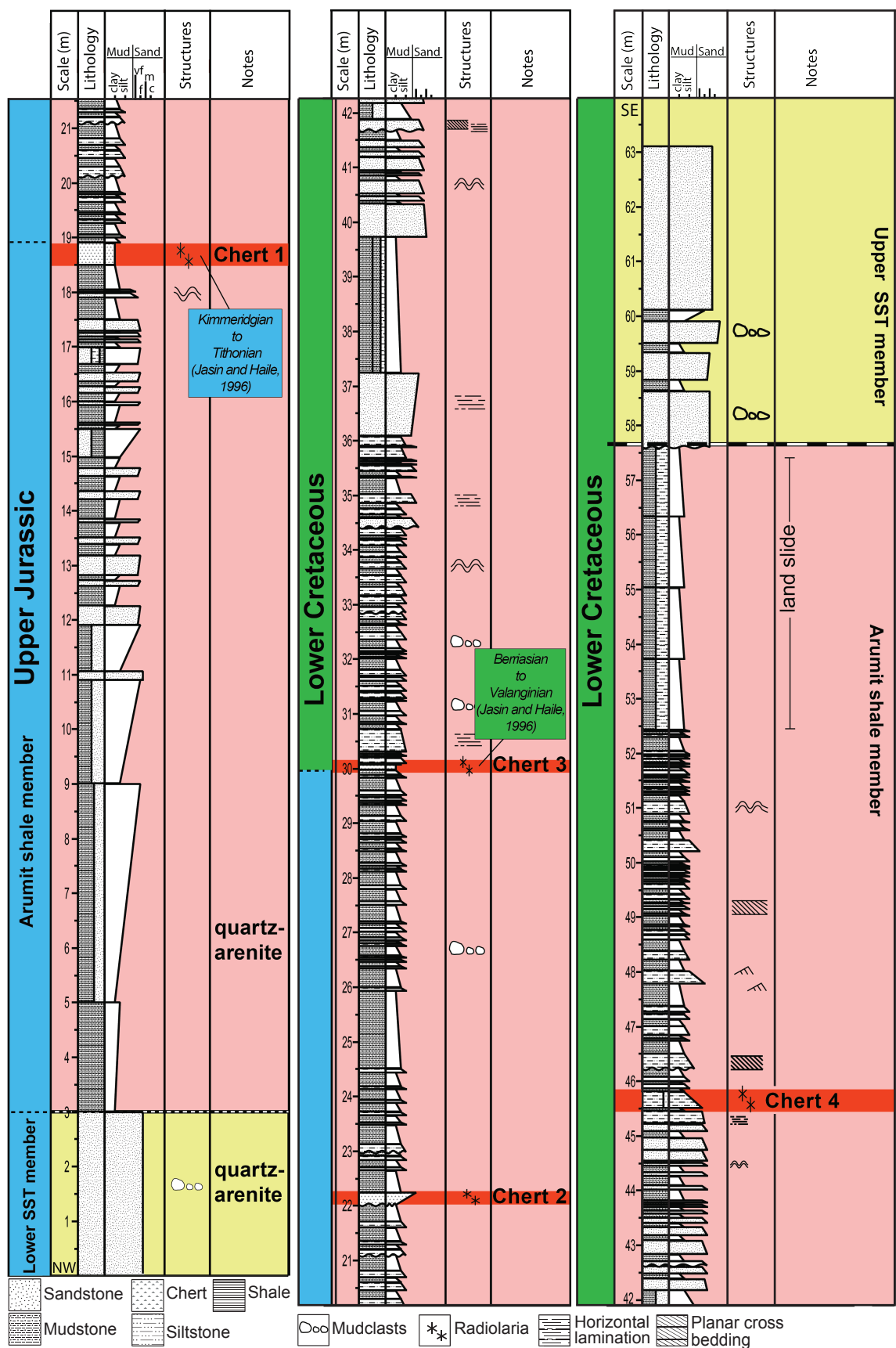


Fig. 7: Sedimentary log of the Arumit Member of the Ungar Formation, showing details of the succession on Ungar Island and its interpreted relationship to the Lower and Upper Sandstone Members. Chert layers are highlighted in red and radiolarian ages are based on Jasin and Haile (1996).

Figure 8

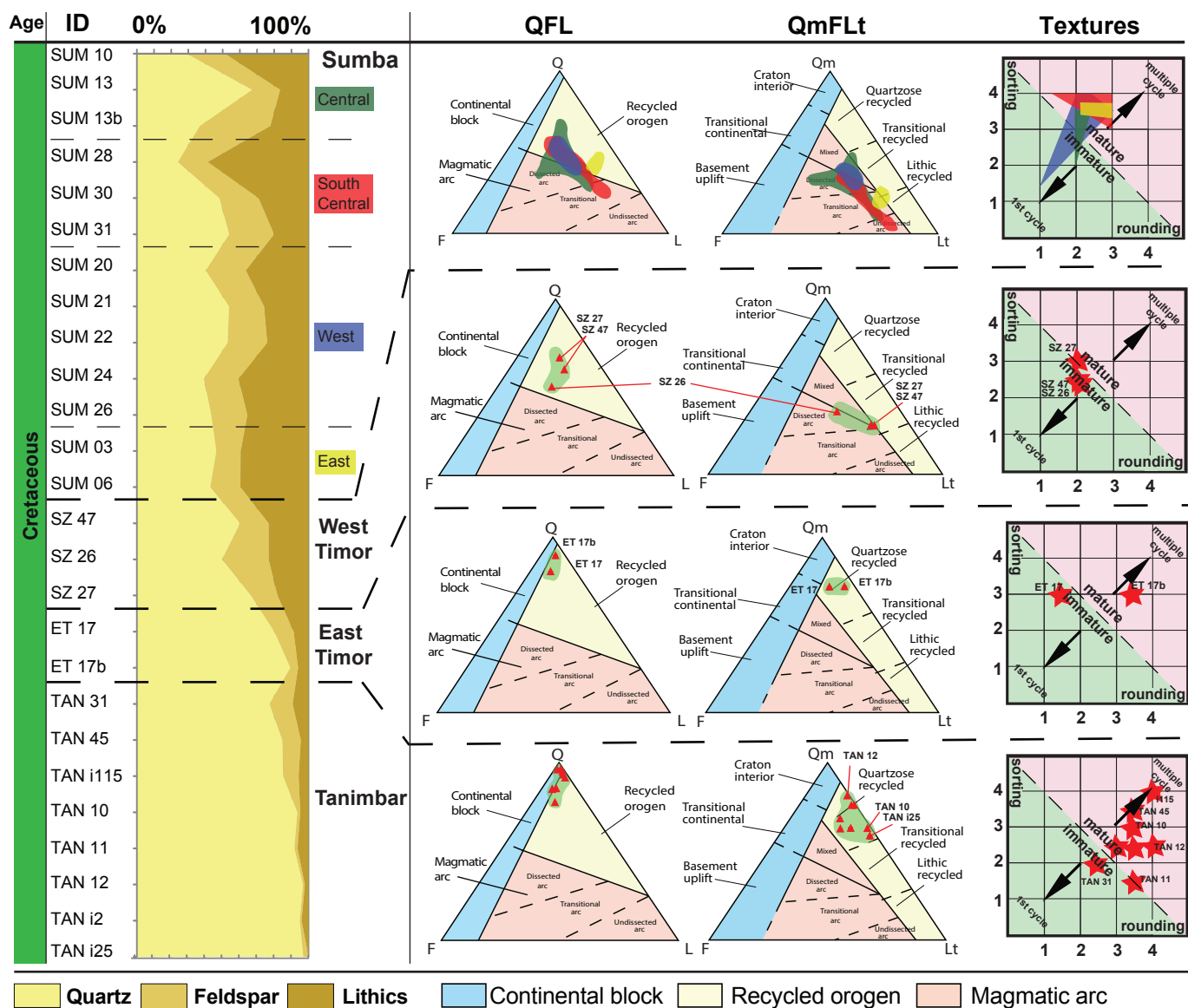


Fig. 8: Summary of light mineral point counting of Cretaceous sandstones from the various islands. Ternary plots after Dickinson et al. (1983) showing possible provenance affiliation (Q – Quartz, F – Feldspar, L – Lithic fragments, Qm – Monocrystalline quartz, Lt – Total lithic fragments). Textures show assessments of sorting and rounding using simple number schemes which were used to estimate maturity.

Figure 9

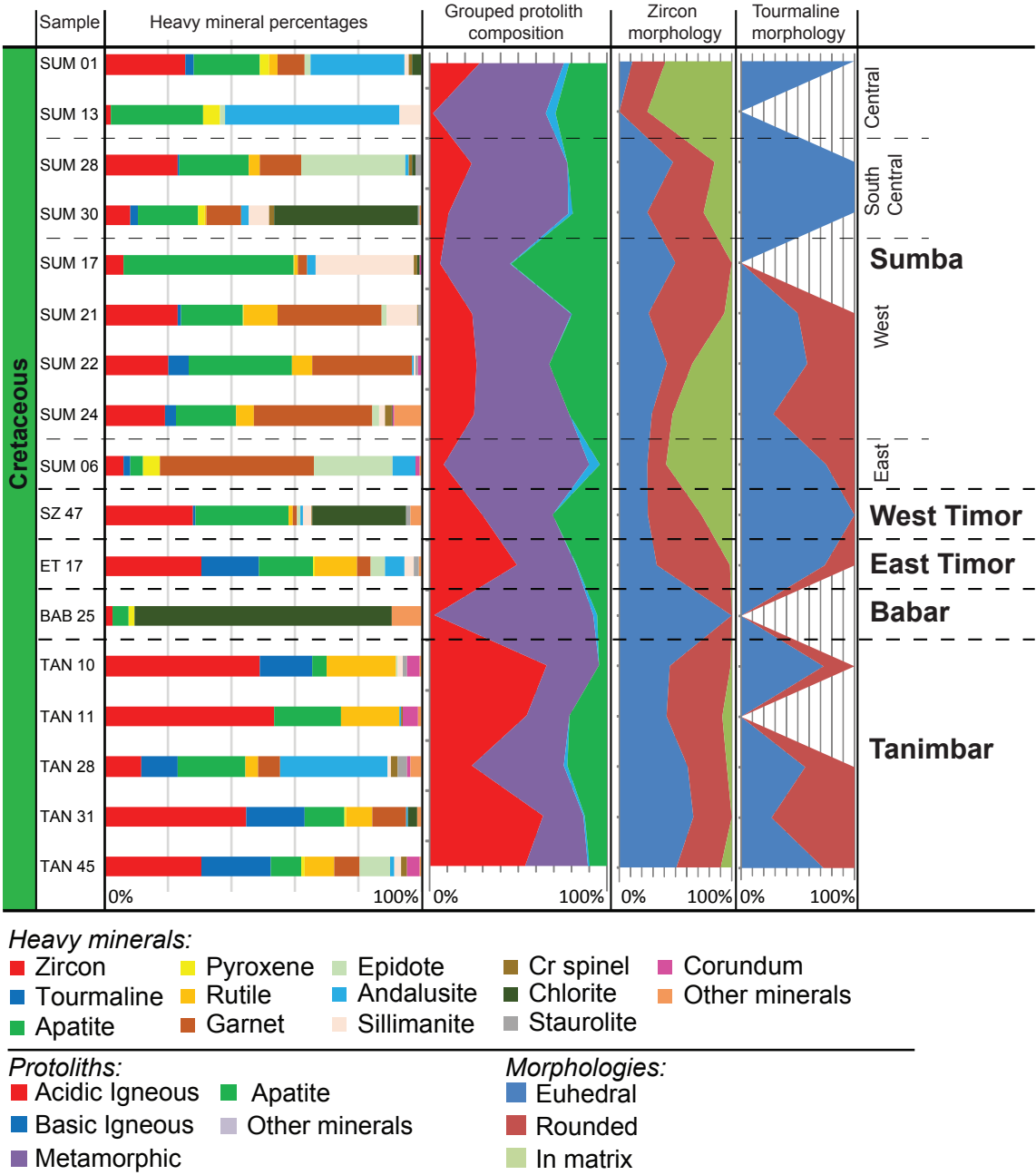
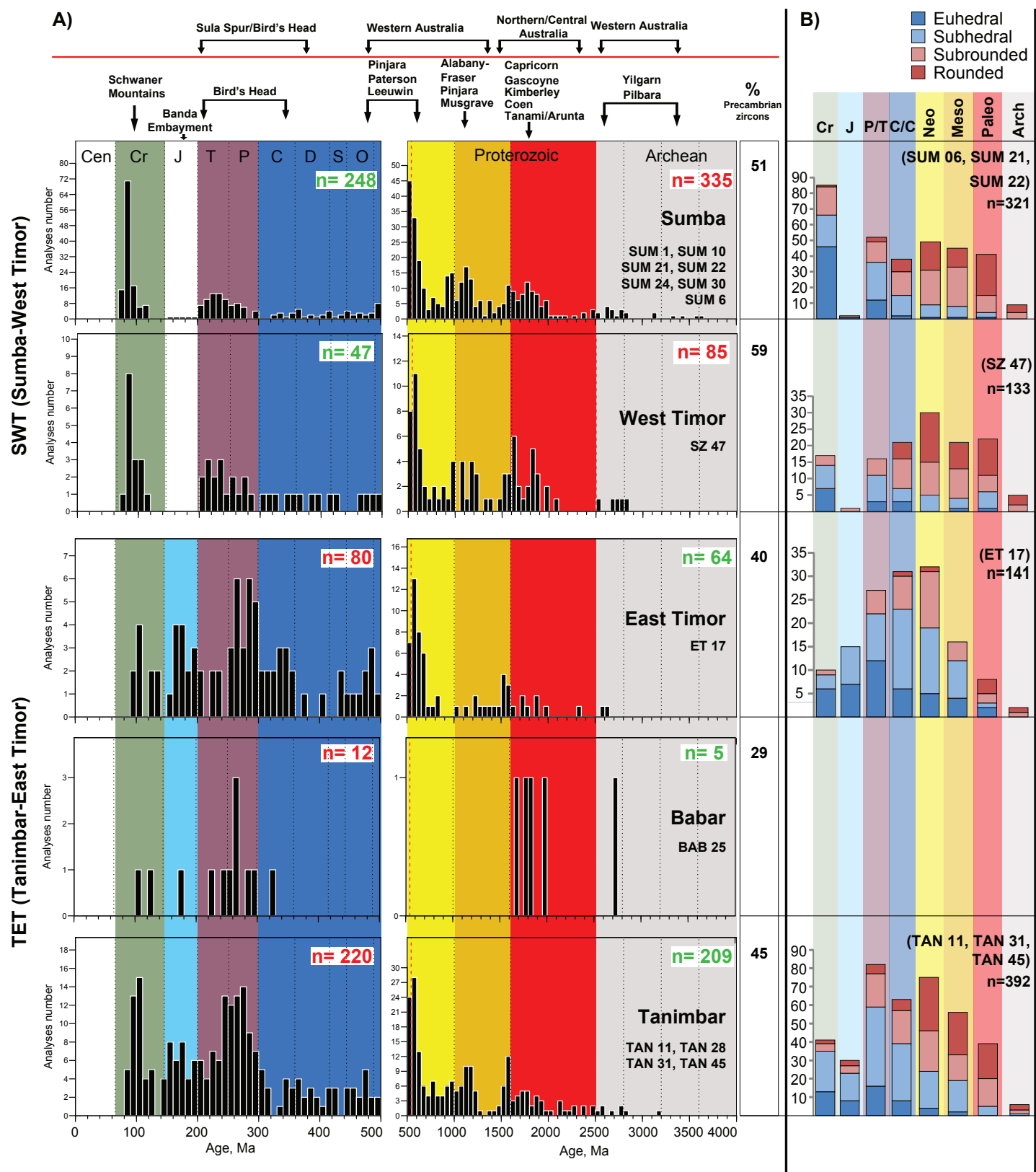


Figure 10



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Figure 11

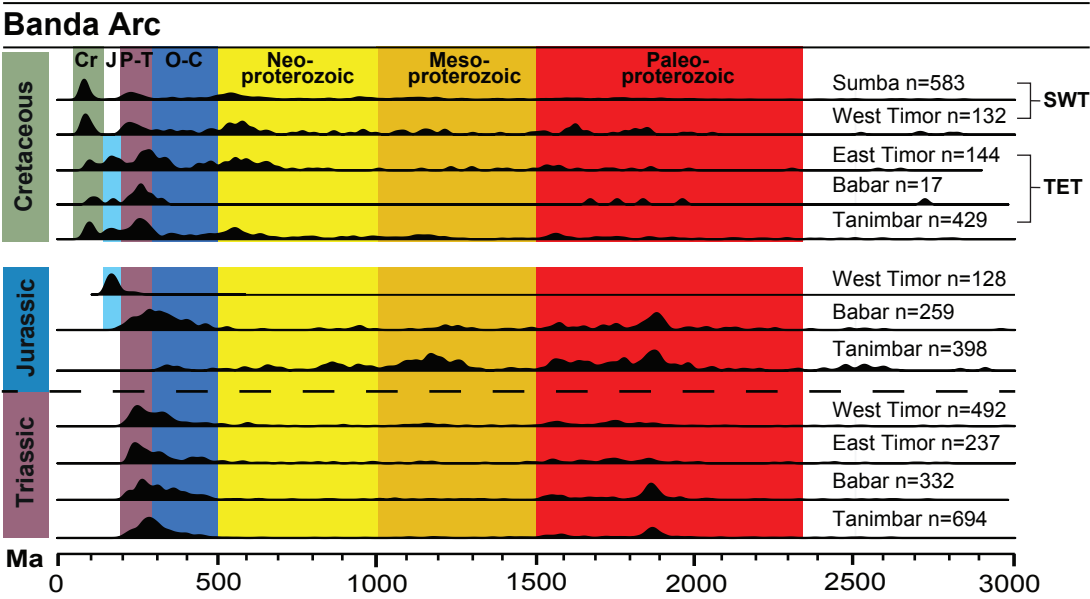


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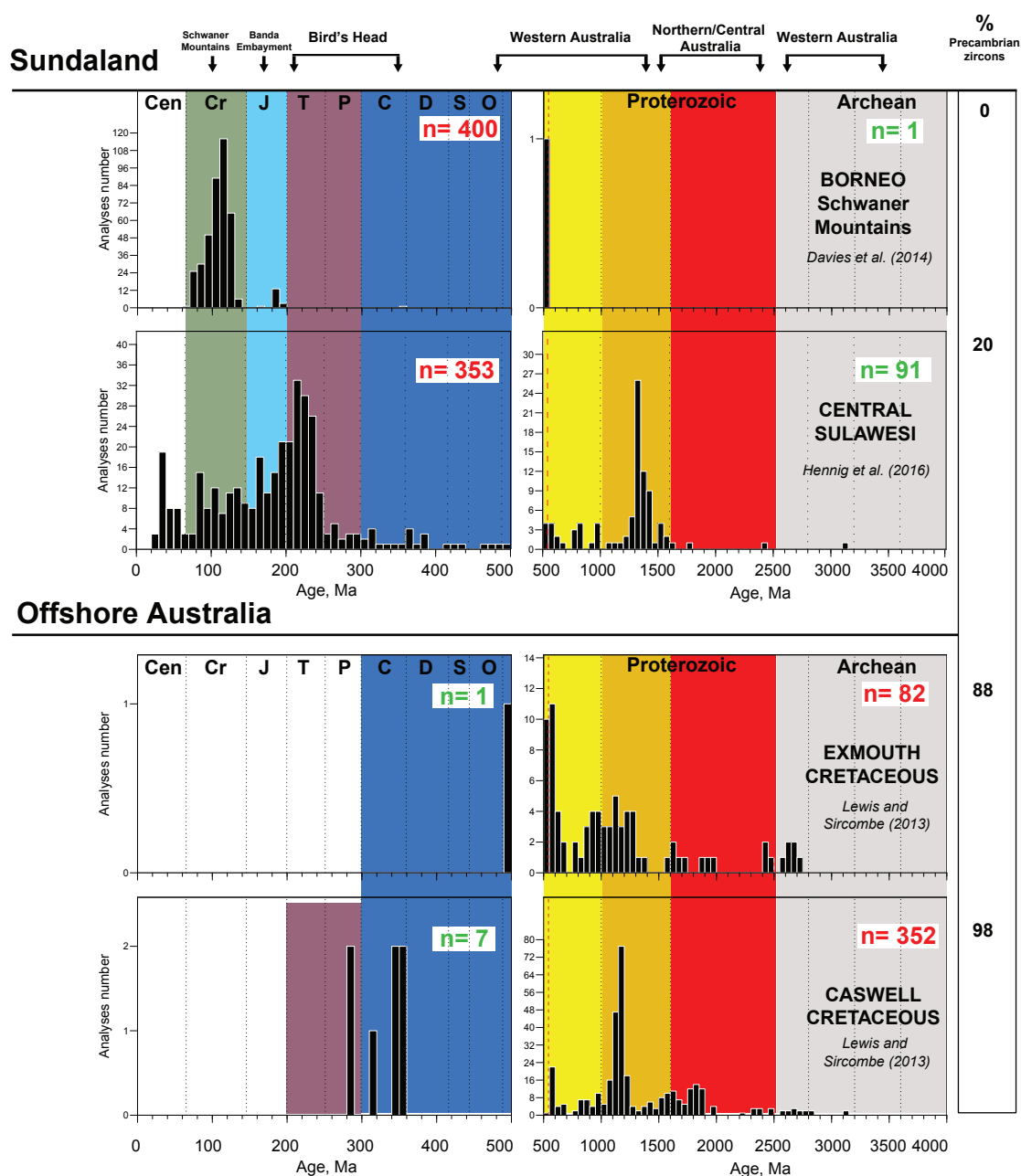


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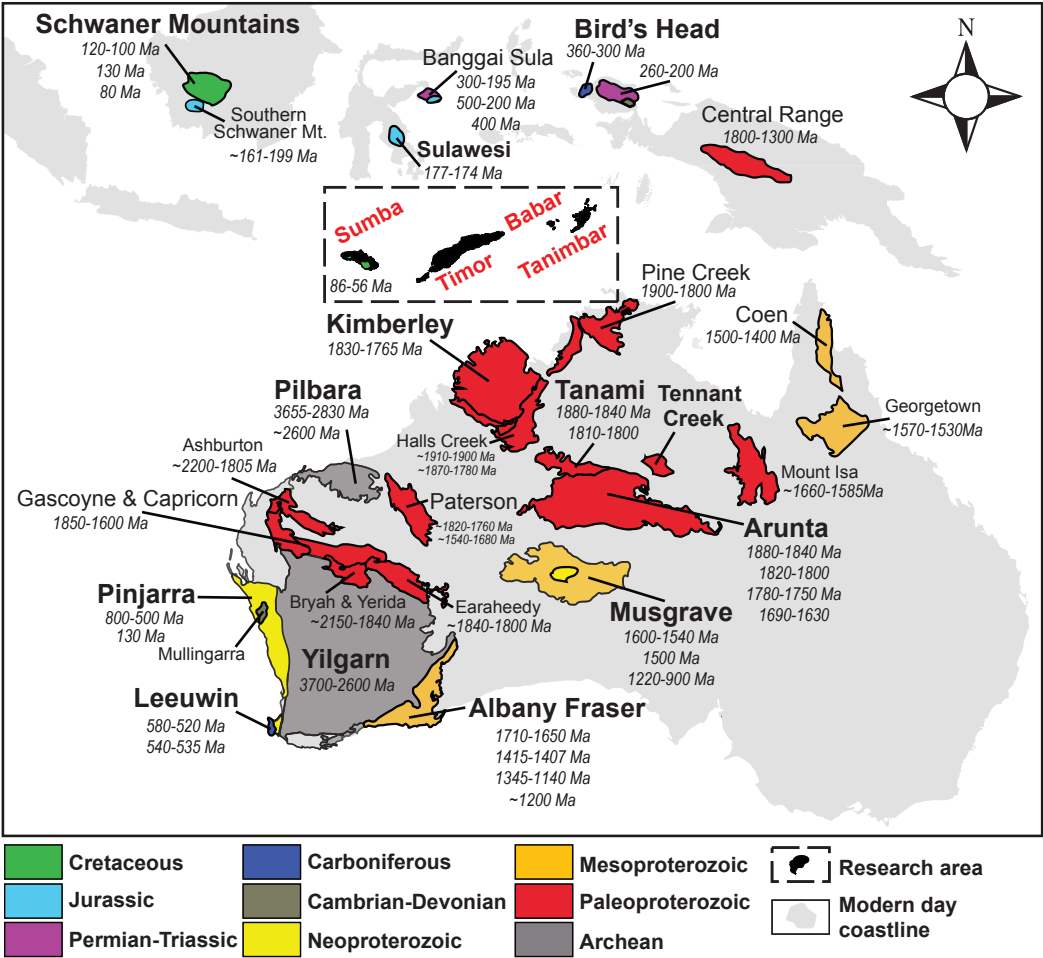


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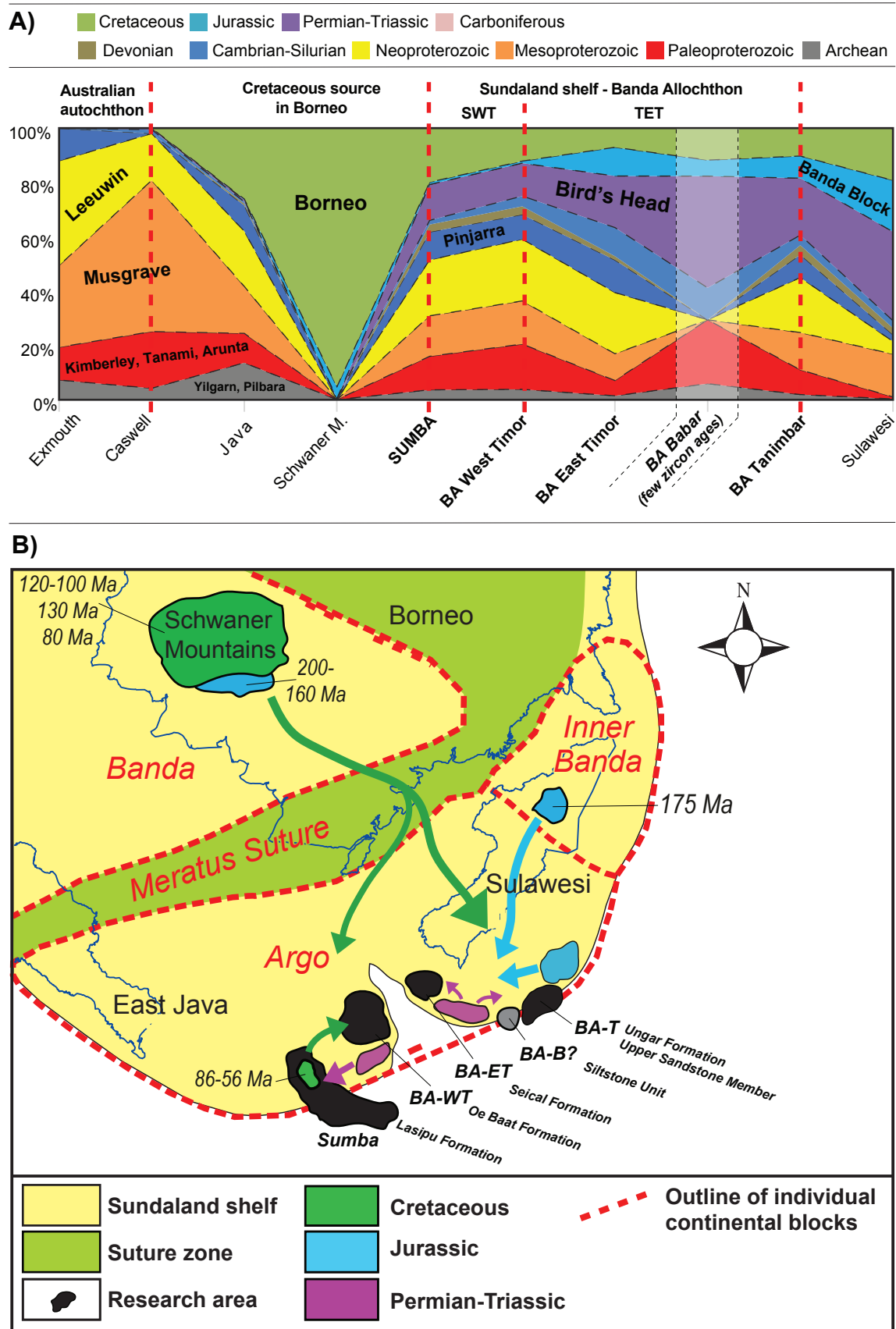


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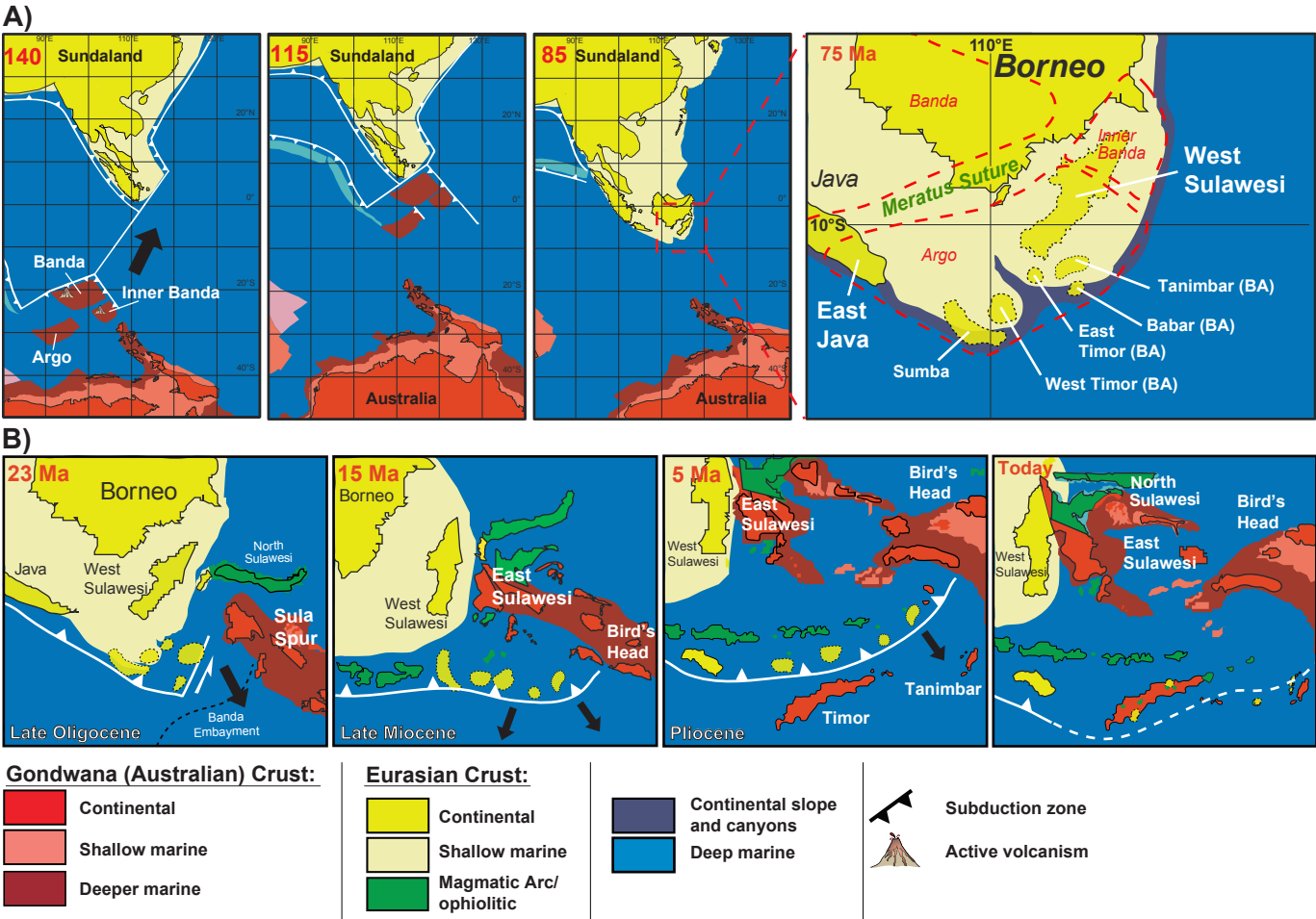


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